New Functional Concept of Valvular Mechanics
in Normal and Diseased Aortic Valves

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SUMMARY
The orifice area of the functioning aortic valve was measured roentgenographically and related to flow across the valve in 27 patients (12 with normal valves). The orifice area of normal valves was linearly related to stroke index and to left ventricular ejection rate. Less than half of the cross-sectional area of the valve was utilized in most patients during the resting state. A larger percentage of the anatomical cross-sectional area was utilized during states of higher flow. Cinematographic studies of porcine valves in vitro showed a comparable flow-dependent orifice size. These results suggest the concept of a functional or physiologic cross-sectional area of the aortic valvular orifice. The anatomic cross-sectional area may be restricted without impingement upon the functional cross-sectional area in states in which flow across the valve is low.

RELIANCE upon anatomic measurements of the aortic valve may induce one to conceive of the aortic valve as if it had a fixed orifice area, affected only by disease. Studies made possible by a roentgenographic technique developed in this laboratory indicate, to the contrary, that the valvular orifice may vary in size and shape, depending upon the functional load imposed upon the valve. Aortograms were obtained by a method specifically adapted to show the aortic valve as if one were looking directly into the orifice. Since the cross-sectional area of the orifice can be measured from these aortograms, the technique was uniquely suited for the study of the functioning valve. Studies in patients were complemented by high speed cinematographic studies of porcine valves mounted to a pulsatile pump. The purpose of this investigation was to determine the relationship between orifice size, configuration, and flow in an effort to increase our understanding of valvular mechanics.

Methods
Studies in Patients
The geometric configuration of the aortic valve during ventricular systole was shown on aortograms by utilization of a projection designed to show the aortic valve as if looking directly into the orifice (fig. 1). As described previously, this was accomplished by directing the X-ray beam through the heart in a line approximately from the right shoulder to the left iliac crest (at a 45° superior elevation in the frontal plane and a 0° elevation in the sagittal plane). In patients with prosthetic aortic valves (with known orifice areas), such films enable measurement of the valvular orifice with less than 10% error in 80% of the patients. Errors of this magnitude (less than 10%) occur due to variability of the orientation of the aortic valve. In patients with an uncommon orientation of the valve, errors greater than 10%
Figure 1

Aortic valvular orifice during ventricular ejection obtained at a roentgenographic projection designed for this purpose. Patient had aortic regurgitation due to Marfan's syndrome. Roentgenographically measured orifice, 5.0 cm² appears triangular. Sinus of Valsalva appears aneurysmal. In the right panel, the orifice is outlined (dotted lines). (Reprinted from Amer Heart J, by permission.)

can occur. Fortunately, such uncommon orientations can be recognized from aortograms or from the position of the catheter. Consequently, such patients would be excluded from study by this technique. Serial roentgenograms were obtained in this projection during the injection of 40 ml of 75% sodium and meglumine diatrizoates (Hypaque-M 75%) at 500 psi in the supravalvular region. Films were recorded at a speed of four per second on an Elema Schonander (Mount Prospect, Illinois) rapid film changer. A catheter with side holes but no end hole was positioned just above the aortic valve. Test injections were made prior to each power injection to be sure that the tip of the catheter was free and well away from the orifice of the coronary arteries.

The exposure time of each film was 0.10 sec. This is important because it is longer than the time required for the valve to open fully from a closed position. Therefore, any films of partial or intermediate openings would necessarily be superimposed upon views of the valve in a completely open or completely closed position. It is likely that the superimposition of images could be recognized as a blurred outline of the valve. Furthermore, films taken over two or three cardiac cycles frequently showed identical openings, which tend to support the validity of the method. Voltage and current varied between 80 and 130 kv and 45 and 60 ma. The radiographic equipment used in this study was North American Philips (Long Island City, New York) powered by a 1000-ma generator.

Figure 2

Relationship of orifice area index to geometric configuration of orifice. Average orifice area index of those with circular-appearing orifices (circle) was larger than those with triangular orifices (triangle). Average area of those with bulging triangular configuration (half circle) was intermediate in size. NS = not significant.
normal aortic valves and 15 with aortic valvular disease. In four of the patients with normal aortic valves, we performed studies during various hemodynamic states (rest, exercise, tourniquets) in order to compare in a single individual the effects of various flows upon orifice size and configuration. Consequently, 16 orifice views of patients with normal aortic valves, all of good quality, were analyzed.

Patients were categorized as having normal aortic valves if there was no diastolic murmur, no basilar systolic murmur of greater intensity than grade I/VI, no pressure gradient measured across the valve, and no calcium in the region of the valve seen with image intensification fluoroscopy. Patients were categorized as having predominant aortic stenosis if the peak pressure gradient across the valve was 35 mm Hg or greater. These patients had clinical and arteriographic evidence of aortic regurgitation as well as stenosis, which would be expected with narrowed and poorly mobile leaflets. There were eight such patients.

Studies in Vitro

High speed cinematographic studies were made of the motion of the leaflets of porcine

Figure 3

Relationship of percent opening of aortic valve to geometric configuration of orifice. Those with circular configurations (circle) had a larger average percent opening than those with triangular configurations (triangle).

The cross-sectional area of the orifice was measured from the roentgenograms by planimetry, and corrected for magnification. The orifice area index was calculated by dividing the cross-sectional area of the valvular orifice by the body surface area. The percent opening of the leaflets was calculated from the ratio of the orifice area to the cross-sectional area of the proximal aorta, as calculated from the roentgenograms. All studies were obtained, with informed consent, at the conclusion of diagnostic left-sided cardiac catheterization.

In patients with normal aortic valves, the geometric configuration and cross-sectional area of the valvular orifice were correlated with stroke index and left ventricular ejection rate. The latter, calculated as the ratio of stroke index to systolic ejection period, was of interest because it indicated the volume of flow across the valve per second of systole. Cardiac output was measured either by the Fick or indicator-dilution technique. The systolic ejection period was measured from photographic recordings of central aortic pressure; pressures were recorded either at 50 or 100 mm/sec.

Twenty-seven patients were studied, 12 with
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Figure 5

Relationship of left ventricular (LV) ejection rate to geometric configuration of valvular orifice. Patients with circular (circle) or bulging (half circle) configurations of the orifice had a larger average ejection rate than those with triangular (triangle) configurations.

Figure 6

Relationship of orifice area index to stroke index. A linear relationship seems to exist. Regression equation, correlation coefficient (r), and probability (P) are shown.

Studies in Patients

In patients with normal aortic valves, the geometric configuration of the orifice during ventricular systole appeared triangular in eight studies, circular in four, and assumed an intermediate or bulging triangular configuration in four. In those with a triangular configuration, the average orifice area index was 1.6 cm²/m² (range, 0.9-2.2 cm²/m²) (fig. 2). In those with a circular-appearing orifice, the average orifice area index was 2.4 cm²/m² (range, 2.1-2.6 cm²/m²) (P < 0.05). Those with an intermediate configuration had an orifice area index of 1.9 cm²/m², which was not significant.

High speed motion pictures were recorded on 16-mm film either at 480 or 1000 frames/sec. Peak opening of the valves was measured by planimetry of the projected image after correction for amplification.

Stroke volume was varied between 10 and 93 ml/stroke. Ejection rate was varied between 15 and 445 ml/sec. Orifice area and percent opening of the valves were correlated with stroke volume and ejection rate.

Results

Studies in Patients

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aortic valves mounted to a rigid model of the left ventricular outflow tract. The model consisted of a Plexiglas flow channel, 2.5 cm in diameter, with simulated sinuses of Valsalva located just distal to the ring of the valve. Isotonic saline or an isoviscous mixture of glycerin and water were pumped through the valves by means of a Harvard Apparatus Company (Millis, Massachusetts) Model 1423 pulsatile pump. Two valves were utilized. Each was sewn to a Shumway ring* of 2.4 or 2.8 cm internal diameter. Maximum possible orifice area, measured with a calibrated cone, was 1.8 and 2.9 cm², respectively.

*Kindly supplied by Cutter Laboratories, Berkeley, California.
AORTIC VALVULAR FUNCTION

\[ y = 0.01x - 0.1 \]
\[ r = 0.86 \]
\[ P < 0.01 \]

Figure 7

Relation of orifice area index to left ventricular (LV) ejection rate. A linear relationship appears to be present. Regression equation, correlation coefficient (r), and probability (P) are shown.

The percent opening similarly was greater in those with a circular-appearing orifice (average, 66%) than in those with a triangular-appearing orifice (average, 40%) \( P < 0.05 \); fig. 3). Those with a circular orifice had a larger stroke index (average, 69 ml/beat/m²) than those with a triangular orifice (average, 42 ml/beat/m²) \( P < 0.05 \); fig. 4). Left ventricular ejection rate was larger in the group with a bulging or circular orifice (average, 210 ml/sec/m²) than in that with triangular orifices (average, 150 ml/sec/m²) \( P < 0.05 \); fig. 5).

Orifice area index was linearly related to stroke index (fig. 6). The orifice area index was also linearly related to left ventricular ejection rate (fig. 7). Similarly percent opening of the valve was linearly related to both stroke index and left ventricular ejection rate.

Orifice views obtained during rest in four patients were compared to those obtained during exercise or with tourniquets around the legs. The orifice in three of four patients appeared larger during states of increased flow (fig. 8). Coincident with the increased orifice area, the valve assumed a more bulging or circular configuration. We are cautious about the significance of these observations because this group of patients was small. Consequently, the validity of these measurements could not be confirmed by statistical analysis.

Finally, two of the patients with normal aortic valves had effective orifices as small as patients with significant aortic stenosis (fig. 9). The stroke indices in those two patients were 27 and 30 ml/beat/m². Their left ventricular ejection rates were 100 and 120 ml/sec/m², respectively.

Figure 8

Aortograms showing aortic valvular orifice in same patient at rest (left) and during exercise (right). At rest, orifice area was 2.5 cm² and stroke volume was 67 ml/beat. The orifice appeared triangular. During exercise, orifice area was 3.0 cm² and stroke volume was 82 ml/beat. The orifice had a bulging triangular configuration.
Studies in Vitro

High speed cinematographic studies of porcine valves mounted to a pulsatile pump showed results comparable to studies in patients. The orifice area and percent opening were linearly related to the ejection rate until a limit was reached, at which point orifice area and percent opening remained constant (figs. 10 and 11).

Stroke volume and percent opening were linearly related only if the ejection period was constant. At a given stroke volume, the valve opening diminished as the ejection period was prolonged (fig. 12).

Maximum opening of either valve was 31%, even with larger stroke volumes and higher ejection rates. The cause of this incomplete opening was not apparent. The valves did not appear to be stiff or abnormal. Results of all of the cinematographic studies were similar with both valves.

Discussion

The fact that aortograms were not timed with hemodynamic events suggests a possibil-

ity that views of the orifice may have been obtained during partial opening or partial closure of the valve. For the following reasons, it is likely that the results of the study were valid, and that significant errors due to the recording of partial openings were not introduced.

1) The duration of the film exposure was 0.10 sec, which is longer than the time required for opening or closure of the valve. Consequently, if a chance roentgenographic exposure during partial opening occurred, it could be recognized by the superimposition of complete opening or complete closure combined with blurring of the leaflets.

2) Intuitively anticipated results of the study were confirmed by statistical analyses. The linear relationship between valve orifice index and stroke index and between valve orifice index and left ventricular ejection rate was significant (P < 0.01). If invalidating errors due to technique were present, random results would be expected.

3) The validity of studies in patients was confirmed by in vitro studies in which cinematographic techniques were used. The utilization of high speed motion pictures eliminated any possibility of
errors due to the recording of partial openings.

The mechanism that controls the variability of size and geometric configuration of the aortic valvular orifice during ventricular ejection appears to be the rate of flow across the valve. A linear relationship seems to exist between the percentage of valvular opening and both stroke index and left ventricular ejection rate. As the orifice increases in size to accommodate a greater flow, the configuration of the orifice assumes a more circular geometric configuration. These results are compatible with the apparently divergent in vitro observations of others. Some investigators, using dissected human aortic valves attached to a pulsatile pump, showed exclusively a triangular configuration of the valvular orifice during systole. These observations agreed with those made in the fifteenth century by Leonardo da Vinci. Others, using model aortic valves, showed a circular orifice. The stroke volume of the pump utilized in those cinematographic studies that showed a circular orifice was two to four times larger than the stroke volume in studies that showed a triangular orifice.

The observations in this study suggest the concept of a physiologic or functional cross-sectional area of the orifice of the aortic valve. The physiologic cross-sectional area, in the resting state of normal individuals, is smaller than the anatomic cross-sectional area. Under states of higher flow across the valve, the physiologic area appears to increase and to approach a limit that is somewhat less than the anatomic cross-sectional area. The aortic valve in the resting state, therefore, has a reserve capability to accommodate larger flow. For example, an average of 60% more cross-section area is available for use in individuals whose orifice appears triangular. Some of this available area is utilized under states of increased flow, such as exercise. Conversely, it seems that the anatomic cross section of the aortic valve could be narrowed nearly 60%
without impingement upon the functional cross-sectional area of the valve during states of low flow.

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